

Material Performance

A degradation study of isotactic virgin and recycled polypropylene used in lead acid battery casings

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Abstract

Polypropylene has become a great concern with regards to environmental pollution since it is generally resistant to normal conditions of degradation. This factor has encouraged the industry to find ways to regenerate spent polypropylene. A good example of such a process is the recycling of lead acid batteries. The use of recycled polypropylene has cost saving implications, but does have a disadvantage in that the material starts to deteriorate after multiple processes. The comparative study investigated the use of various ratios of virgin and different grades of recycled PP in the manufacturing of lead acid battery cases and their influence on its physical and chemical properties. The degradation of PP was also investigated as the material was subjected to multiple manufacturing processes where the influence of stabilizers was considered. A common technique used for the analysis of PP, MFI was shown to be an effective technique to maintain a good quality control system within the battery case manufacturing process. The study further showed that it is important to maintain a compatible grade of PP for both the battery case and lid in order to allow for effective heat sealing of the two components.

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Keywords: Recycled polypropylene; virgin polypropylene; Lead acid battery; MFI**1. Introduction**

Polypropylene (PP) is one of the most commonly used plastics and very versatile in its use and application in the polymer industry. The material was developed in the early 1950's using Ziegler type catalysts and has since gained enormous attention where no other polymer encompasses its versatility in physical properties, regarding its ease of manufacturing and its use in many applications [1,2]. The polymer is a thermoplastic and can be heated to a melt in a matter of minutes and molded into a variety of shapes and sizes

with great ease. The material is also resistant to oxidation or environmental degradation and has its application in a variety of corrosive environments. However, the latter highlights one of the greatest disadvantages of polypropylene regarding its impact on waste disposal in the environment, where it can only be disposed of properly by incineration [3,4].

In the materials short life span, the means of trying to recycle polypropylene has become a priority according to the American Plastics council [2,4]. As the polymer gets reused, the number of times it is processed (reheated and remolded) starts to influence a number of properties, such as its impact and tensile strength, durability, color, appearance and impurity levels in the final product [2,4].

Mechanisms for the degradation of PP are usually complicated and depend mostly on the processing

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environment and the level of exposure experienced during the application [5]. In general, free radicals are created when the polymer chains are exposed to mechanical stress, thermal energy and catalytic residues. These free radicals ($R^\cdot$) form via hydrogen removal from the labile tertiary carbon [6,7].

Oxygen molecules that are trapped between the PP pellets during the feeding process of the extruder can act as the trigger for the autooxidation cycle. Macromolecules react with the oxygen to form peroxy radicals ($ROO^\cdot$), which interact with the polymer chains to generate hydroperoxides ($ROOH$) and more free radicals ($R^\cdot$). Decomposition of hydroperoxides ($ROOH$) can occur easily to form hydroxyl ($O^\cdot H$) and propoxyl radicals ($RO^\cdot$). These in turn can further react with or break molecular chains. Termination of these radical reactions occurs via a deactivation process and can take place at any time of the cycle in the presence of stabilizers. These act as ‘radical scavengers’ and consist mainly of sterically hindered phenols molecules, hydrolytically stable phosphates or sterically hindered amine stabilizers [6,7].

Rheological measurements of recycled materials can be effectively used to determine the amount of processing and chain scissions a polymer has experienced during the recycling process. From rheology, the molecular weight averages of the chains can be calculated and used as a guideline to processing parameters of polymers [7–13]. This is not always the preferred method, as rheometers are expensive with lengthy experimental time. The results are often difficult to explain and have to be done by experienced analysts. Melt flow indexing (MFI) is an easier and quicker technique and can be related to the values obtained from more sophisticated rheological measurements. In general, materials with a high MFI value relate to a polymer with short-chained molecules and a polymer with long chained molecules would tend to give a low MFI value. However, since MFI is only one single value, it gives limited understanding of the flow properties of the plastic with significant room for error if analysis is not done properly. The values can range between 1 and 200 g/10 min for polypropylene [1,6]. The MFI values for lead-acid battery casings made from virgin material would generally range between 8 and 9 g/10 min and battery casings made from recycled material would be about 12 g/10 min.

The battery manufacturer requires the battery housing to have a relatively high impact resistance over a wide range of temperatures (-32 – 80 °C) and to mould effectively around protruding lead terminals [14]. A critical process during the manufacture of the

battery is the formation of a good bond between the plastic lid and case, which is done by heat sealing. A problem encountered in the sealing process is where, for example, a black recycled PP battery case is bonded to a clear or colored virgin PP lid. This often results in the formation of a poor bond between the two dissimilar polymers and is related to the flow properties of the two polymers and their ability to withstand the high temperatures that occur during the process. A common practice is to restrict the use of recycled PP by using a mixture of virgin and recycled material in the manufacturing of the components.

Although many studies of the use of recycled PP in the manufacturing of various components have been done [11], none have addressed the situation specific to lead-acid battery casings of heat sealing of dissimilar PP grades and the use of an easy and reliable technique such as MFI to maintain good manufacturing quality control.

The study investigated the use of recycled PP in lead acid batteries and its influence on the physical and flow properties of the material, especially with regards to the heat sealing ability of different grades of polypropylene. Further, the influence of multiple recycling and the use of suitable stabilizers in polypropylene were investigated. An automotive battery is a consumable and has a product life expectancy of between 3 and 4 years. Hence, the material used for the battery housing would be subjected to a number of recycling processes which would impact on the usability and performance of the material in the manufacturing of new cases. The study considered the feasibility of using a relatively simple technique, such as MFI, for the purpose of quality control in an industrial environment to determine the amount of recycled material within battery casings and, possibly, to give an indication as to how often the material had been recycled.

2. Experimental

2.1. Degradation study

A sufficient amount of clear virgin isotactic polypropylene was subjected to one cycle of recycling by injection molding suitable test pieces using a Toshiba 350-ton injection-molding machine with the barrel set at 245 °C and the mold at ambient temperature. The pieces were reground and enough sample was taken for analysis and the molding of impact and tensile test pieces. The rest of the sample was then subjected to further recycling by injection molding and regrinding. This was done for nine

cycles, with suitable amounts of material taken at each step for analysis. The same procedure was repeated using a batch of recycled black polypropylene that contained approximately 1.0% of a commercial stabilizer that was made up of antioxidants and co-additives. The virgin and recycled polypropylene materials were graded according to their initial MFI values of 8.5 and 10.7 g/10 min, respectively. The samples were analyzed by the methods discussed below.

2.2. Virgin and recycled polypropylene ratio study

Recycled polypropylene pellets were sourced from different suppliers and can be classified as follows:

- Recycled polypropylene that contains relatively short-chained molecules and will be described as ‘short recycled’ with an initial MFI of 12.3 g/10 min.
- Recycled polypropylene that contains relatively medium chained molecules and will be described as ‘medium recycled’ with an initial MFI of 11.4 g/10 min.
- Virgin polypropylene, that is highly isotactic and corresponds to a MFI of 8.5 g/10 min.

Samples were prepared by mixing ratios of 20, 40, 60 and 80% (by weight) of recycled and virgin material respectively. The mixed samples were injection molded on an Arburg small volume injection molder into various test pieces for impact and tensile testing. The barrel of the injection molder was set at 180 °C and a die temperature of 210 °C. The mould was kept at ambient temperature. Each of the samples were left to condition for 48 h before analysis by the following methods.

2.3. Characterization methods

2.3.1. MFI

The MFI analysis was done on a Hanatek 4010 melt flow indexer according to ISO 1133 with an extrusion weight of 2.16 kg and a barrel temperature of 230 °C.

2.3.2. Rheology

The polypropylene samples were heated with a mantle to just above the melting point of polypropylene (190 °C) and analyzed in the melt on an Anton Paar Rheometer using a 25 mm diameter plate–plate geometry. Frequency sweeps were performed on each sample and the storage modulus (G'), and loss modulus

(G'') were recorded from 100 to 0.1 rad/s. To determine the MWD, the relaxation time spectrum, $h(\tau)$, was estimated from the measured data, i.e. the dynamic shear moduli, $G'(\omega)$, $G''(\omega)$ and reported in kilogram per mole [12,13].

2.3.3. Tensile testing

Tensile test pieces were injection-molded and analyzed on a Hounsfield tensometer using a 5 kN load cell and crosshead speed of 50 mm/min (at 25 °C) according to ISO 527. A maximum of five samples were tested per batch and the average value reported in MPa.

2.3.4. Impact strength

Test pieces were injection molded where each sample was first notched and then analyzed using an Izod impact tester with a 7.5 J pendulum according to ISO 180/1A. The tests were performed four times and the average value reported in kilojoule per square meter.

2.3.5. FTIR (Fourier transform infrared)

Representative pieces were taken from each of respective polypropylene samples and pressed into thin films at 140 °C and with a pressure of 3 ton. The resulting thin films ranged between 50 and 90 μm and were analyzed using a Bruker Tensor 37 FTIR. The samples were scanned in absorbance mode from 400 to 4000 cm^{-1} and their spectra recorded. The extent of the oxidation of polypropylene can be evaluated by determining the relative amounts of carbonyl groups present in the material [5,7]. The carbonyl group is observed at 1750 cm^{-1} and normalized by dividing by an observed peak at 3100–3250 cm^{-1} . This was done in order to take slight variations in film thickness into consideration.

2.3.6. Sealing ability

Samples of the mixed ratio polypropylene were melt-bonded to the commercially sourced polypropylene with a MFI of 0.81 g/10 min. This was done in order to investigate the sealing ability of various combinations of virgin and recycled polypropylene to a dissimilar material. Samples of diameter 100 mm $\times$ 20 mm $\times$ 3 mm were melted at 370 °C for 5 s and then pressed together for 8 s, using a special heat sealing mechanism. The bonded samples were then tested for their bond strength using a Hounsfield Tensometer. The tests were carried out at 25 °C using a crosshead speed of 50 mm/min after the samples had been left at 25 °C for 48 h.

3. Results and discussion

3.1. Multiple recycling of virgin PP and stabilized PP

3.1.1. Flow characteristics

The multiple processing of polypropylene generally leads to the degradation of the material via a chain breaking mechanism. Melt flow index (MFI) can be a useful method to describe how much processing or degradation a polymer had experienced if the MFI and composition of the starting material is known. The results in Fig. 1 shows that the MFI of virgin PP and stabilized PP increased linearly as the material was subjected to a number of recycle processes.

The respective R^2 values of the linear relationships for the virgin and stabilized PP were 0.98 and 0.88. The MFI for the virgin PP with recycled number increased more rapidly than the stabilized PP. This indicates that the stabilizer contained within PP reduced the formation of radicals and decreased the amount of chain breaking the polymer experienced. By comparing the slopes of the straight-line graphs, the MFI values of the virgin PP increased by a factor of 1.7 times greater than the stabilized PP over the nine recycle processes investigated.

The specified MFI for recycled PP used in the manufacturing of battery cases should be below 12 g/10 min. However, the MFI for the virgin PP after four cycles was already 13.5 g/10 min and after nine cycles was almost twice that of the specified value. This indicates that there is a limit to the number of recycling the PP battery case can be subjected to in order for the material to remain within the manufacturers specifications.

The rheological analysis of the various multiple recycled PP samples showed that the calculated average molecular weight (Mw) for the polymers decreased with recycling number (Fig. 2). Noticeably, a large Mw

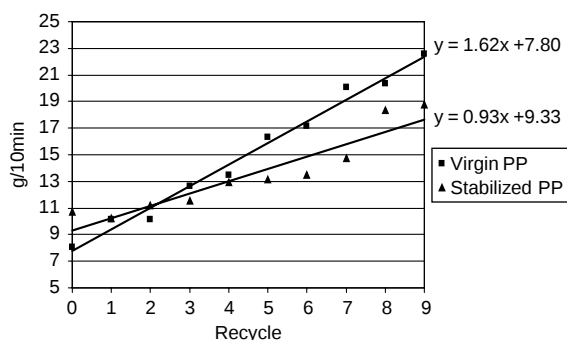


Fig. 1. MFI values versus recycle number for virgin PP and stabilized PP.

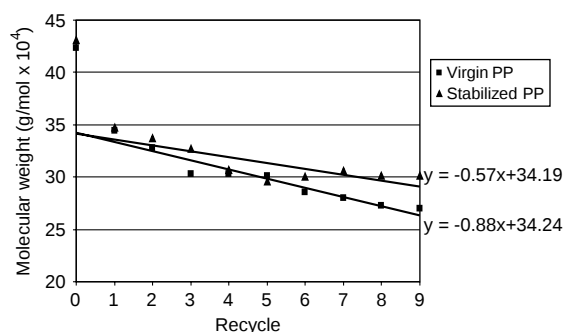


Fig. 2. The average molecular weight distribution versus recycle number of virgin and stabilized PP.

decrease of about 16% was observed for the first cycle, after which a smaller but linear decrease in the molecular weight was observed for subsequent cycles. The results relate to the MFI values obtained for the respective polymers, which showed an increase with recycling number. The increase in flow and decrease in molecular weight implies that scissions of the molecular chains had occurred as a result of the recycling process [5]. The linear equations shown in Fig. 2 were determined by excluding the zero cycle values and the respective R^2 values for the virgin and stabilized PP are 0.92 and 0.70.

Two distinctive weight distributions of polypropylene were observed when the whole molecular weight data of the virgin and stabilized PP are considered (Figs. 3 and 4). Values for the molecular weight distribution below 40 kg/mol were not obtained, since these were impractical in terms of requiring significant longer analysis time on the rheometer. The data of each of the molecular weight distributions were deconvoluted using a peak fit program and an example is shown in Fig. 5 [15]. The integrated peak areas showed that the two observed peaks decreased with recycling number,

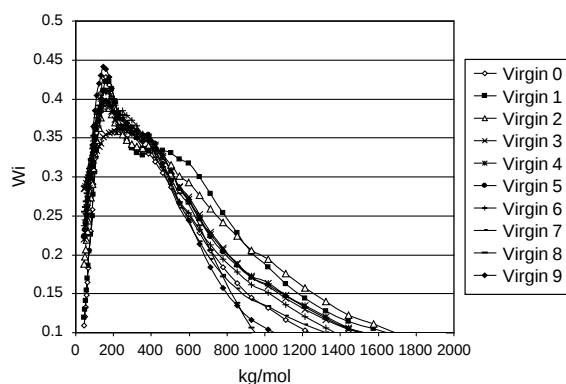


Fig. 3. Molecular weight distributions for the respective cycles of virgin polypropylene.

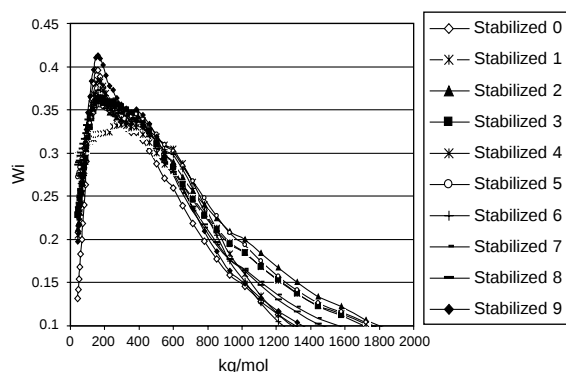


Fig. 4. Molecular weight distributions for the respective cycles of stabilized polypropylene.

which implied that the relative amounts of the two weight distributions became less, as the polypropylene was recycled (Fig. 6). The respective slopes of the straight line equations showed that the decrease of the stabilized PP peak at 400 kg/mol with recycling number was almost 1/2 the rate when compared to the virgin PP peak at 400 kg/mol, whereas the comparative decrease of the peak at 170 kg/mol for the two PP samples studied were similar. This implies that the stabilizer helped to retain relatively longer chain molecules within the polymer matrix, whereas shorter chain molecules would be more susceptible to degradation during the recycling process.

3.1.2. Physical and chemical characteristics

The repeated recycling of battery casings influences the physical and chemical properties of the polymer and if no suitable stabilizers are added to the material with a good manufacturing quality control system, problems can occur that can lead to inferior products with an increased amount of waste. The comparative study of

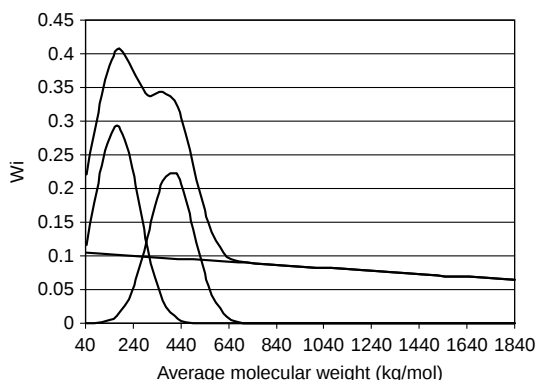


Fig. 5. Best Gaussian peak fit of the deconvoluted results for the molecular weight distribution for the zero cycled virgin polypropylene.

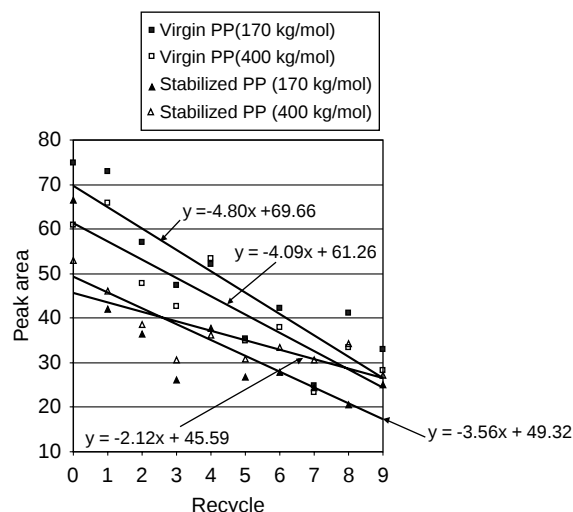


Fig. 6. The integrated areas of the deconvoluted peaks for the molecular weight distributions for the respective recycles of virgin PP and stabilized PP.

the physical property changes of virgin PP and stabilized PP showed that the tensile strength and elongation at maximum yield decreased as the respective polymers are repeatedly processed. In general, multiple processing of polypropylene causes molecular chains to undergo chain scissions due to mechanical stresses and the formation of free radicals during the autooxidation step of melting. Scission of the larger molecular chains increases the number of shorter chains of the respective polymer, which would lead to fewer entanglements and thereby decrease the tensile strength and percentage of elongation (Fig. 7). Noticeably, the virgin PP had initially a higher tensile strength than the stabilized PP. However, the tensile strength results of the two polymers samples were almost similar in value after about three to four

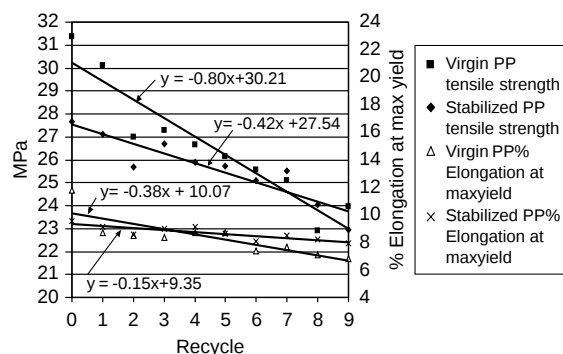


Fig. 7. Tensile strength and percentage of elongation (at max yield) versus process number of virgin and stabilized polypropylene.

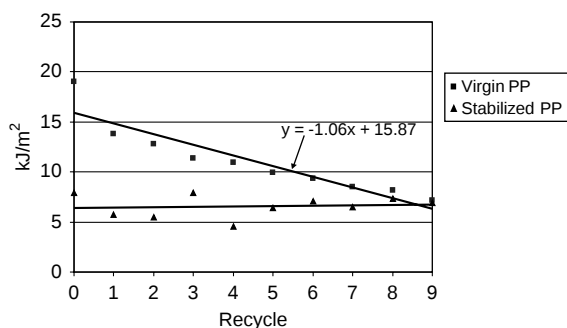


Fig. 8. The impact strength of virgin PP and stabilized PP versus recycle number.

recycling processes with very little change in the respective percentage of elongation.

The impact strength of the virgin PP was initially larger (more than twice) than the corresponding strength of the stabilized PP (Fig. 8). With subsequent recycling, the impact strength of the virgin PP decreased linearly whereas the strength of the stabilized PP remained relatively unchanged over the nine recycles steps. The impact strength of the virgin PP was also similar in value to the stabilized PP after the nine recycles step. Impact resistance in polymers is often related to the crystallinity of the material. The higher the crystallinity, the lower the impact strength where there are many factors that can contribute to the crystallinity of a polymer, not only the length of the respective polymer chains. Even though the relative molecular chain lengths of the stabilized PP decreased with recycle number, the additives that are dispersed within the bulk material must have given the material an inherent consistent crystallinity (chain ordering) over a certain distribution of molecular chain lengths.

A relatively good correlation was obtained between the MFI ($R^2=0.88$), impact strength ($R^2=0.95$), tensile strength ($R^2=0.85$) and the changing average molecular weight of the virgin PP due to multiple recycling (Fig. 9). Over the range of the molecular weight studied, the change in the respective MFI was considerably more sensitive to changes in average molecular mass than the respective tensile and impact strengths. If the material is relatively homogeneous, an estimation of the average molecular weight, its tensile and impact strengths can be obtained by determining the MFI of the material. However, this is impractical in the study of recycled PP, where a large range of stabilizers and unknown additives could be present. This is shown in the correlation between the MFI, tensile and impact strength with the average molecular weight for the stabilized PP (Fig. 10). Noticeably,

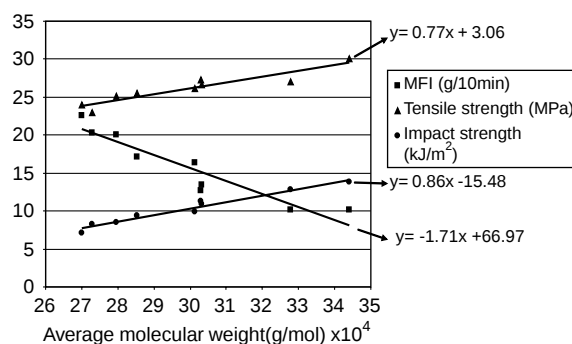


Fig. 9. The relationship between the tensile, impact strength, MFI and molecular weight of the respective recycles of virgin polypropylene.

the impact strength of the PP with the stabilizer did not change with increasing average molecular weight and the linear correlation with the MFI and tensile strength were considerably poorer ($R^2=0.41$ and 0.49). The recycled material containing the stabilizer and other additives would have influenced the change in physical properties with respect to the average molecular weight significantly differently than for pure virgin PP.

Each respective recycle of virgin and stabilized PP was analyzed by FTIR and the peak areas at 1750 cm^{-1} regarding the carbonyl groups was determined. The normalized oxidation peak areas are plotted against recycle number and are shown in Fig. 11. The results show that the process of repeatable grinding and injection molding of virgin PP does not necessarily increase the carbonyl group content (oxidation). This is in agreement with literature that reported that an increase in the oxidation in many cases would only be observed after processing 17 or more times at a temperature of 270 °C [5]. However, some literature reported that oxidation was observed after eight cycles of processing at 240 °C for virgin polypropylene [7]. The carbonyl group of the stabilized PP decreased after

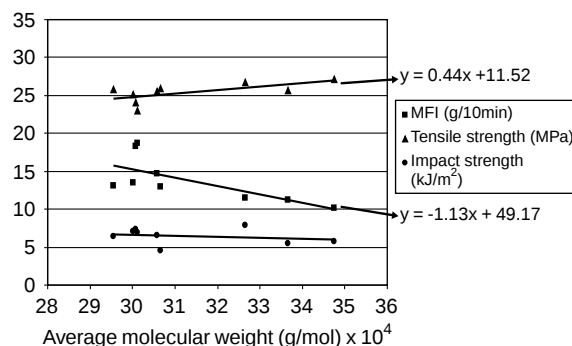


Fig. 10. The relationship between the tensile, impact strength, MFI and molecular weight of the respective recycles of virgin polypropylene.

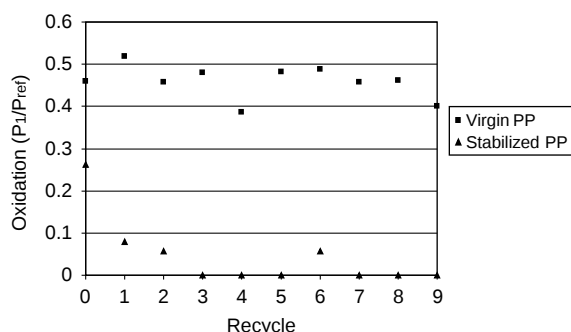


Fig. 11. Normalized peak areas for the oxidation peaks obtained for respective recycles of virgin and stabilized PP.

the first few recycling steps and generally disappeared as the amount of recycling was increased. This implies that the addition of the stabilizer to polypropylene seems reduce the formation of the carbonyl group content of the recycled PP.

3.2. Virgin and recycled polypropylene ratio study

3.2.1. Flow characteristics

A range of flow characteristics can be obtained for polymers using rheology, where information such as the relative molecular weight of the polymer chains can be calculated. The rheological data for the polypropylene grades used (short chained PP, medium chained PP and virgin PP) were calculated from the rheological frequency sweeps shown in Fig. 12 and are summarized in Table 1.

The frequency sweeps for the various grades of polypropylenes showed that the medium chained recycled material were similar in their rheological properties to that of the virgin PP. The short-chained PP recycled material, however, showed a decrease in the gradients of the storage modulus (G') and loss modulus (G'') curves.

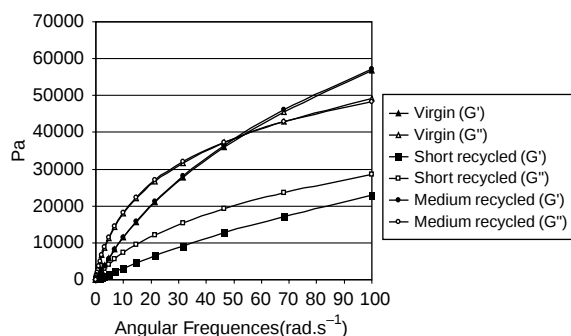


Fig. 12. Rheological frequency sweeps for virgin, short recycled and medium recycled polypropylene.

Table 1

Calculated molecular weight data for the short recycled, medium recycled and virgin polypropylene

Type	Average (Mw)	PDI
Short recycled	283900	–
Medium recycled	405200	2.756
Virgin PP (MFI=8.10 g/10 min)	423100	2.924
Virgin PP (MFI=0.81 g/10 min)	463600	2.329

Considering the storage modulus of a polymer, a curve with a small gradient generally relates to a polymer with a wide molecular weight distribution and vice versa for a large gradient. The difference in the gradient of the storage modulus (G') for the short chained recycled PP when compared to the other materials, showed that it had the widest molecular weight distribution.

Table 1, shows the average molecular weight and PDI (polydispersity index) for the starting materials. PDI generally refers to the width of the polymers molecular weight distribution. A low value such as 2, generally indicates a narrow molecular weight distribution. Table 1 shows that Medium recycled, Virgin PP (MFI=8.10 g/10 min), Virgin PP (MFI=0.81 g/10 min) had relatively narrow molecular weight distributions, whereas the molecular weight distribution for the short recycled material was so wide spread that a PDI value could not be determined.

The MFI results of the various ratio samples prepared with different grades of recycled material added to virgin PP show a relatively linear increase with increasing concentration of recycled material to that of virgin polypropylene (Fig. 13). The MFI values obtained for the samples containing short chained recycled PP were slightly higher than that for medium chained recycled PP. Straight-line equations were obtained for the above results with good R^2 values of

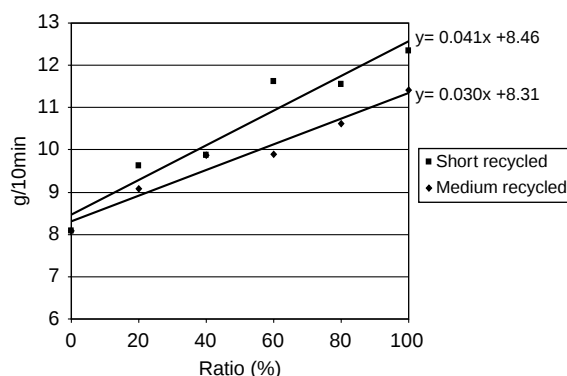


Fig. 13. MFI values obtained for ratios of short recycled and medium recycled PP with virgin polypropylene.

0.93 and 0.96 for the short chained and medium chained recycled PP with virgin PP. This implies that if the MFI of the virgin PP and the particular recycled PP is known before injection molding a battery case, a good estimation of the percentage of recycled material in the final product can be determined by measuring its MFI.

3.2.2. Physical and chemical properties

The strength of polypropylene is generally related to the length and entanglement of the polymer chains. The expected tensile strength of virgin polypropylene would be greater than that of recycled material. By varying the amount of recycled material with virgin polypropylene during manufacture, the strength of the polymer should be generally affected as shown in Fig. 14.

The results show that a slight decrease in tensile strength occurs when recycled PP is added to virgin material. Recycled PP that contains shorter chain molecules generally gave lower tensile strength values when compared to medium chain recycled PP when mixed with virgin PP. For small additions (20%) of recycled to virgin PP a decrease of about 14% in the tensile strength was observed. The initial drop in tensile strength is the result of short molecular chains acting as a lubricant or solvent between the longer molecular chains. This leads to a decrease in the density of the material and less entanglement of the respective chains [10]. However, when the recycled material was increased, only a slight increase in the respective tensile strength and percentage of elongation was observed.

A slight increase in the impact strength was observed when small amounts of recycled material are added to virgin PP (Fig. 15). However, for samples that contain above 60% recycled material a decrease in impact strength was observed. In general, the impact

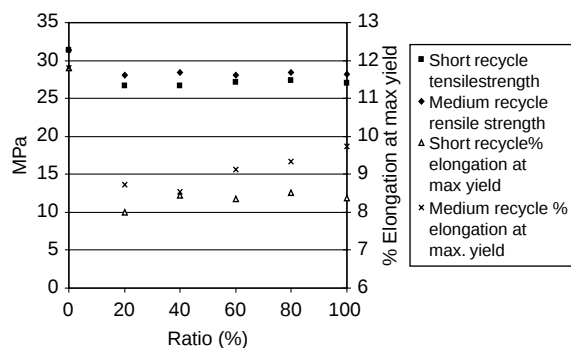


Fig. 14. The tensile strength and percentage of elongation (at maximum yield) of varied amounts of short chained recycled and medium chained recycled with virgin PP.

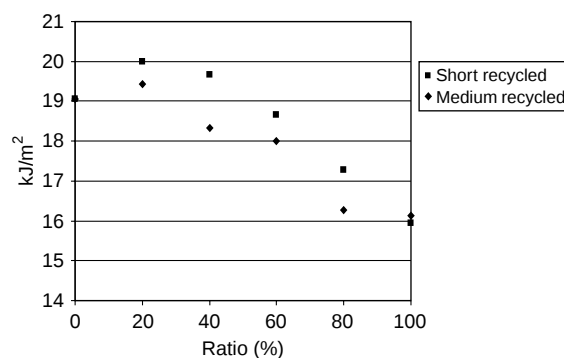


Fig. 15. Impact strength of short recycled and medium recycled with virgin PP.

strength of polypropylene decreased as the amount of recycle PP was increased when compared to the 100% virgin PP sample. The initial slight increase in impact strength could have resulted from a decrease in the polymer's crystallinity that was initiated by the shorter chained molecules of the recycled PP that act as lubricants between the larger virgin PP chains [10].

Fig. 16 shows the change in carbonyl content of the various mixed ratios of recycled and virgin PP. Noticeably, the virgin PP used contained a higher amount of carbonyl (oxidative) groups than the respective recycled materials. The relative oxidation shows a constant decrease in oxidation for the respective polymer ratios as the amount of recycled material was increased. It is not certain whether the recycled polypropylene used for this study could have already contained long term heat stabilizers, which would account for the observed lower carbonyl group content.

3.2.3. Sealing ability

In order to investigate the heat sealing of dissimilar PP materials in terms of their MFI value, a grade of

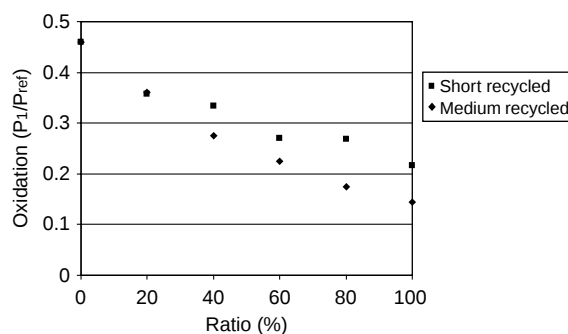


Fig. 16. Normalized peak areas for the oxidation peaks obtained for varied amounts of short recycled and medium recycled with virgin polypropylene.

polypropylene was used that had a MFI of 0.81 g/10 min. Rectangular shape samples of different ratios of recycled material (short and medium chained) to virgin PP were melt-bonded to similar sized strips made from the low MFI polypropylene. The strength of the melt-bond, which simulates the lid to case sealing of a lead acid battery, was determined by tensile testing. Even though the material is regarded as a polypropylene, it showed some considerable differences in terms of its chemical and physical properties. In discussion, the two virgin PP used will be referred to by their respective MFI values. Rheological molecular weight distributions of the virgin PP used are shown in Fig. 17. The Mw for the virgin PP (MFI of 0.81 g/10 min) was 46.36×10^4 g/mol whereas the other material had a Mw of 42.31×10^4 g/mol (Table 1).

The results in Fig. 18 show that the sealing of the two virgin polypropylenes (MFI of 8.5 and 0.81 g/10 min) gave the lowest bond strength of 16 MPa. In comparison, when the PP with a MFI of 0.81 g/10 min was heat sealed to itself, the resulting bond strength was almost doubled at 30 MPa. This bond strength is similar to that of virgin PP that contained no recycled material, which was shown previously in Fig. 14. The samples that contained as little as 20% recycled PP improved the bond strength by 37% showing that an improvement in the flow properties of the polymers results during the heating process. Hence, the use of recycled PP allows for more compatible sealing, thereby improving the bond strength. Very little difference in bond strength was

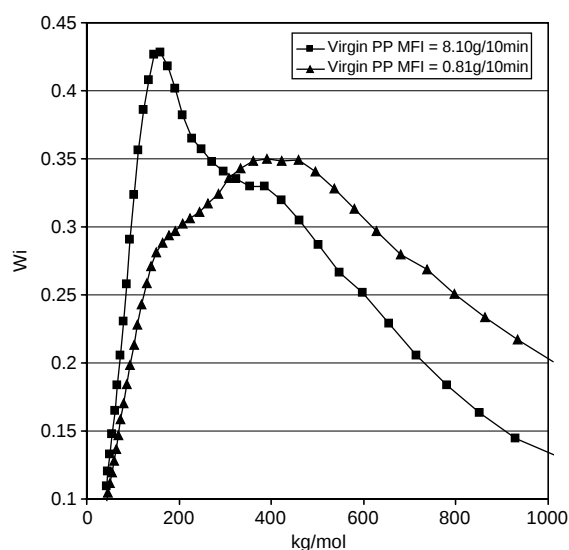


Fig. 17. The molecular weight distributions of virgin polypropylene with a MFI of 0.81 g/10 min and 8.10 g/10 min, respectively.

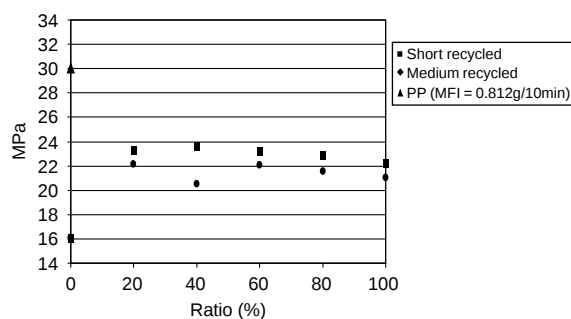


Fig. 18. Bond strength of virgin (MFI 8.5 g/10 min) and the various ratios of recycled polypropylenes to virgin polypropylene (MFI 0.81 g/10 min).

observed for the other mixed ratio samples that were heat sealed to the virgin PP. The samples containing the shorter chained recycled PP gave on average slightly higher bond strength. This could be due to the presence of the shorter chain molecules acting as a lubricant during the heating and bonding process, allowing for a better bond, or entanglement to occur between the different polymer types.

The results indicate that heat sealing of dissimilar PP in terms of their MFI value can be improved by adding small amounts of recycled material, even if the material has a relatively high MFI value in comparison to the virgin PP samples used. A number of other factors would also contribute to the formation of a good heat seal between two polymer samples. These include the extent of the holding times against the heating platen and its temperature. The temperatures of typical heating platens are often above 370 °C where carbonizing of the material can occur, thereby weakening the heat sealing bond.

4. Conclusion

The use of the common technique of MFI was shown to be a quick and reliable method to determine the flow properties of polypropylene used in the manufacture of lead acid battery cases.

The MFI and rheological studies of recycled polypropylene that contained a stabilizer showed a significant improvement in terms of maintaining long-term polymer stability, in particular of the longer chain molecules within the polymer matrix.

Spectroscopic analysis showed that the chain scission, which occurs in polypropylene during recycling, is mainly as a result of heat and mechanical shearing and does not generally occur due to oxidation of the polymer.

If a particular battery case is made from a mixture of virgin and recycled PP, MFI was shown to be successful technique for the determination of the amount of recycled material present, as long as the MFI values of the initial virgin and recycled PP are known.

The study showed that a slight decrease in the tensile strength of a battery case containing a mixture of virgin and recycled PP does occur with varying amounts of recycled material. However, it was found that small additions of recycled material with virgin PP initially increased the impact strength of the material, but tended to decrease as the amount of recycled material was increased.

It was shown that the heat sealing of virgin polypropylenes with very different MFI values would result in poor sealing of the battery case. However, a small amount of recycled material seemed to improve the heating sealing ability by acting as a lubricant between the larger molecules. It is therefore, important to ensure compatibility of the materials used in terms of their MFI and molecular weight distributions in order to ensure good sealing of the battery lid and cover.

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